

An investigation into the differing efficiencies of working fluids used in binary cycle power plants.

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Abstract: In this paper the efficiency of three common working fluids in binary cycle geothermal power plants were compared by modeling the properties of the fluid within the working parameters of the Dora-II geothermal power plant. It was concluded that ammonia has the highest efficiency of the fluids and R-134a was the least efficient.

Keywords: geothermal power efficiency; R-134a; n-pentane; ammonia; working fluid; Dora-II; geothermal; binary cycle; Rankine; geothermal power plant

Nomenclature

R-134a	1,1,1,2-tetrafluoroethane	\dot{m}_G	Mass flow rate of geothermal fluid
η_I	First Law efficiency	h_n	Specific enthalpy at point n in simple Rankine cycle
ϵ	Cycle efficiency	T_n	Temperature at point n in simple Rankine cycle
η_{II}	Second law efficiency	s_n	Specific entropy at point n in simple Rankine cycle
\dot{m}_w	Mass flow rate of working fluid		



1. Introduction

Non-renewable power, such as coal fired power plants, are by nature a limited energy resource. They are limited by both the amount of resources available to be used to fuel power generation and the detrimental effects that the by-products of these plants have on the earth. The major renewable sources are wind, solar, hydro-electric, and tidal power. These sources have restrictive properties that limit where and how often they can produce energy. Wind, solar and tidal power are inconsistent in times that they can generate power as they are reliant on favourable conditions to produce power. Renewable power sources such as wind turbine plants require wind that is strong enough to turn the blades but not so fast as to burn out or cause excessive stress on the turbine itself, severely limiting the conditions that they are effective in. (1,2) Solar is in a similar position in that it requires light from the sun to be incident on the panels to be able to produce power. (1) This limits the operation times to during the day and efficiency can be reduced by cloud cover. The energy in the light from the sun, i.e., areas further away from the equator go through periods of large reductions in incident light as well as decreased energy due to the thicker atmosphere. Tidal power is limited to the number of times the tide changes a day to produce the power. Whilst this is both regular and predictable if the flow of tidal water increases above the operational speed of the generator then the system can be damaged if it is not shut down preemptively. Whilst these systems can have greater efficiency for power production than geothermal plants, they have lower consistent power generation when compared to fossil fuel, nuclear and geothermal power. Geothermal power stations can maintain a consistent level of power output as they are not reliant on atmospheric conditions, the location of the sun, or the position of the moon to generate power. As long as the location chosen can produce enough hot water then power generation will be consistent day or night all year round.

The performance of a geothermal power plant is limited by the temperature of the geothermal water. A standard geothermal power plant that uses geothermal water as the working fluid requires water temperatures with a minimum reservoir temperature of 180°C. (2) The minimum temperature for geothermal power is set so that when the water reaches the turbines it has been converted to superheated steam and expands fast enough to drive the turbine. To increase the spread of geothermal powerplants, binary cycle systems have been developed. These plants use a closed loop with a working fluid that is not water to generate the power. The working fluids used in these systems are chosen because they have lower boiling points and lower specific heat capacity compared to water (5,6). These fluids are used in binary systems as their low boiling points allow the fluids to be in a gaseous state at lower temperatures than water, thus being able to drive a turbine at lower temperatures. This allows binary powerplants to be built in areas with lower reservoir temperatures that currently range

from 70°C to 250°C. (2) The fluids that are currently being used in current production plants include 1,1,1,2 Tetrafluroethane (R-134a), ammonia and n-pentane. (5,6,7) One property that is present in ammonia that is not in R-134a or n-pentane is that when in significant concentration, as is present in this simulation, is that ammonia is very corrosive. Ammonia is know to corrode copper- and zinc-containing alloys as well as attacking rubber and plastics. (3)

2. Methods

The purpose of this research is to determine to what degree the working fluid impacts the efficiency of a binary cycle geothermal power plant.

Plant efficiency was modelled using the equations used by Subbiah and Natarajan (4).

$$\eta_I = \frac{(Turbine\ work) - (Pump\ work)}{(Input\ heat)} = \frac{\dot{m}_W(h_4 - h_5) - (h_3 - h_2)}{\dot{m}_G(h_6 - h_7)} \quad Eqn. [1]$$

$$\epsilon = \frac{Net\ output\ work}{Available\ energy\ input\ to\ rankine\ cycle} = \frac{\dot{m}_W(h_4 - h_5) - (h_3 - h_2)}{\dot{m}_G(h_6 - h_7) - T_0(s_6 - s_7)} \quad Eqn. [2]$$

$$\eta_{II} = \frac{Net\ output\ work}{Overall\ available\ energy\ between\ T_6\ and\ T_0} = \frac{\dot{m}_W(h_4 - h_5) - (h_3 - h_2)}{\dot{m}_G(h_6 - h_7) - T_0(s_6 - s_0)} \quad Eqn. [3]$$

Where η_I is the first law efficiency, ϵ is the cycle effectiveness and η_{II} is the second law efficiency.

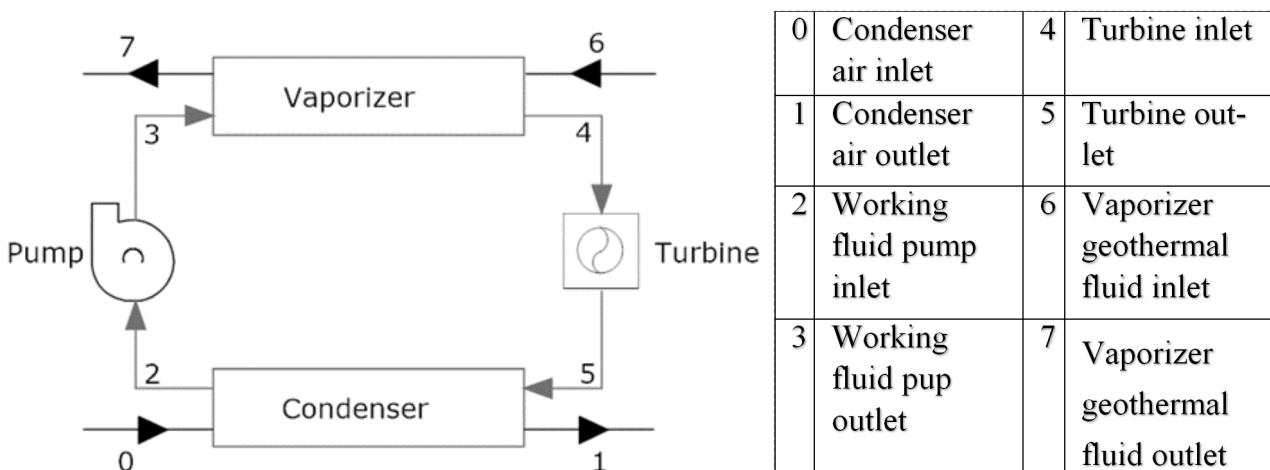


Figure 1. Simple Rankine cycle process

These equations are matched to a simple binary cycle geothermal power plant (see figure 1). Using these equations and data researched from papers. The effects of the three fluids was compared by using

the current working fluid in the production plant then using the same brine and condenser data, and changing the enthalpy and entropy data for each fluid. The enthalpy and entropy was calculated using the Fluid Property Calculator from the International Refrigerant Consortium. (5) The fluid data in table 1 was sourced from Aylward & Findlay’s SI Chemical Data 7th edition (6) and from the GESTIS substance database (3) The data in table 2 was taken from the paper by Ganjehsarabi et al. (7) That data was then used as the basis for calculating the efficiencies of R-134a and ammonia. The mass flow rate, temperature and pressure were kept as constants for the plant. The calculated data is shown in table 3 and 4.

The efficiency was also graphed against the price per kg of the fluids. The prices were obtained from Alibaba.com, as it supplies in commercial amounts.

The fluids chosen for this paper were restricted to ones that are currently being used in power plants that are currently supplying power for consumers.

3. Results and Discussion

The fluid comparison was based on a combination between the operational specifications of the Dora-II geothermal plant in Turkey and the simplistic Rankine cycle. We can see from the results that ammonia is more efficient than n-pentane and R-134a. The efficiency is noted to be a result of the amount of change in enthalpy between the stages in the Rankine cycle. When the efficiency was graphed against the price per kg of the fluid it was seen that ammonia is again the best option for a working fluid in this plant.

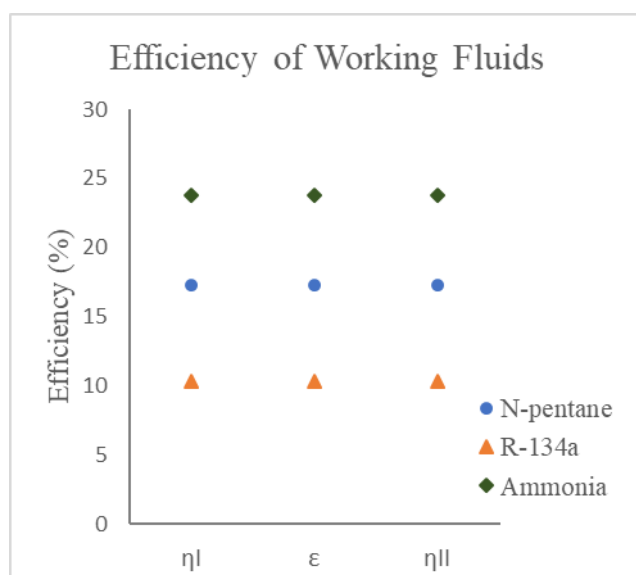


Figure 2. Comparison of working fluid efficiency.

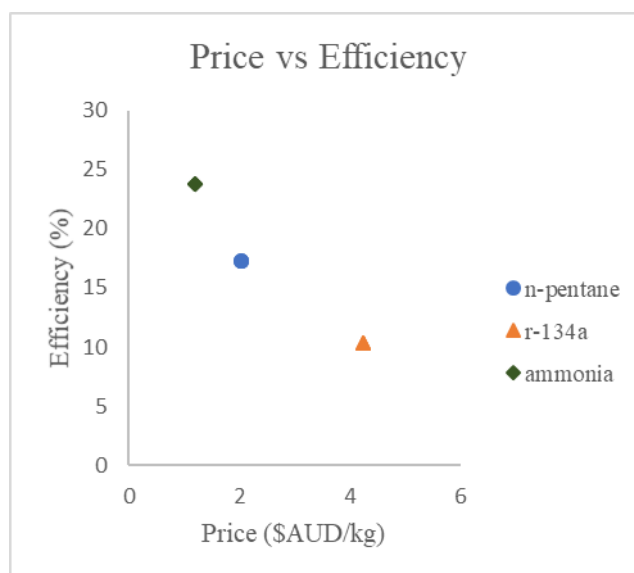


Figure 3. Graph of price against efficiency of the working fluids

4. Conclusions

A comparison of the fluids show ammonia as the most efficient of the three fluids investigated. This indicates that to achieve a higher level of efficiency at the Dora-II power plant the working fluid of n-pentane should be replaced by ammonia. However, using ammonia will be more expensive in up keep as it is more corrosive than n-pentane and R-134a. This puts the plant at a higher risk of leaks and reduction of efficiency. Leaks will be of great concern when running both ammonia and n-pentane as they are both flammable. From that perspective, R-134a would be a more suitable fluid as it is not corrosive and is not readily flammable. It is not recommended to replace the working fluid with R-134a, as it will greatly reduce the efficiency of the plant. Therefore, n-pentane is the best choice for a long term working fluid. It will reduce the cost of maintenance compared to ammonia and has a higher efficiency than R-134a. It was also concluded that the working fluid can have a theoretical impact on efficiency of 13%.

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Appendix

Properties	Fluid		
	R-134a	N-pentane	Ammonia
Mol Mass (g/mol)	102.03	72.1	17
Specific heat capacity (gas) (J/(K*mol))	87	120	35
Boiling point (Celsius)	-26.3	36.1	-78
melting point (Celsius)	-103.3	-129.7	-33
flash point (Celsius)	none	-49	630

Table 1. Table of working fluid properties

		Fluid	Phase	Temperature (°C)	Pressure (kPa)	Specific enthalpy (kJ/(kg*K))	Specific entropy (kJ/kg)	Mass flow rate (kg/s)
Point in simple rankine cycle	0	Air	Gas	17.1	1013	290.25	1.67	4350
	1	Air	Gas	29.1	1013	302.3	1.71	4350
	2	n-pentane	Liquid	41.87	141.85	20.66	0.065	118.61
	3	n-pentane	Liquid	89.3	1185.5	133.88	0.39	118.61
	4	n-pentane	Vapour	133.08	1185.5	510.23	1.33	118.61
	5	n-pentane	Vapour	83.7	141.85	444.46	1.38	118.61
	6	Brine	Liquid	169	1296.96	715.11	2.03	231.94
	7	Brine	Liquid	124.4	1296.96	523.15	1.57	231.94

Table 2. Data for n-pentane at each stage of the simplistic Rankine cycle

		Fluid	Phase	Temperature (°C)	Pressure (kPa)	Specific enthalpy (kJ/(kg*K))	Specific entropy (kJ/kg)	Mass flow rate (kg/s)
Point in simple rankine cycle	0	Air	Gas	17.1	1013	290.25	1.67	4350
	1	Air	Gas	29.1	1013	302.3	1.71	4350
	2	R-134a	Liquid	41.87	141.85	290	1.12	118.61
	3	R-134a	Liquid	89.3	1185.5	322	1.05	118.61
	4	R-134a	Vapour	133.08	1185.5	368	1.18	118.61
	5	R-134a	Vapour	83.7	141.85	329	1.24	118.61
	6	Brine	Liquid	169	1296.96	715.11	2.03	231.94
	7	Brine	Liquid	124.4	1296.96	523.15	1.57	231.94

Table 3. Data for R-134a at each stage of the simplistic Rankine cycle.

		Fluid	Phase	Temperature (°C)	Pressure (kPa)	Specific enthalpy (kJ/(kg*K))	Specific entropy (kJ/kg)	Mass flow rate (kg/s)
Point in simple rankine cycle	0	Air	Gas	17.1	1013	290.25	1.67	101.83
	1	Air	Gas	29.1	1013	302.3	1.71	101.83
	2	Ammonia	Liquid	41.87	141.85	1560	6.27	118.61
	3	Ammonia	Liquid	89.3	1185.5	1630	5.47	118.61
	4	Ammonia	Vapour	133.08	1599.58	1740	5.75	118.61
	5	Ammonia	Vapour	83.7	438.5	1650	6.54	118.61
6	Brine	Liquid	169	1296.96	715.11	2.03	231.94	
7	Brine	Liquid	124.4	1296.96	523.15	1.57	231.94	

Table 4. Data for ammonia at each stage of the simplistic Rankine cycle.